Magnetostriction of single crystal and polycrystalline $Tb_{0.60}Dy_{0.40}$ at cryogenic temperatures

J. A. Dooley, C. A. Lindensmith, R. G. Chave
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA

N. Good, J. Graetz, B. Fultz
California Institute of Technology, Pasadena, USA

polycrystal

At cryogenic temperatures, TbDy alloys exhibit giant magnetostriction, which makes these materials interesting for engineering service in cryogenic actuators, valves, and positioners. A saturation magnetostriction of 8800 ppm has been measured at 10 K for single crystal $Tb_{0.60}Dy_{0.40}$, but the preparation of single crystals is difficult and will likely remain so. Textured polycrystalline materials are being developed for use in place of single crystals and the preliminary results are presented here. For instance, polycrystalline $Tb_{0.60}Dy_{0.40}$, plane-rolled (one direction of applied stress) to induce crystallographic texture, has shown magnetostrictions at 77 K of 3000 ppm for an applied field of 4.5 kOe and an applied load of 41 MPa, or 48% that of a single crystal. Comparisons are presented between the plane-rolled and form-rolled (two orthogonal directions of applied stress) polycrystalline $Tb_{0.60}Dy_{0.40}$ magnetostrictive response for both 10 K and 77 K. The temperature dependence of the magnetostriction in the 10-77 K range will be discussed as well. Even with half of the single crystal performance, however, the polycrystalline samples show two major advantages. First, they are easy to prepare, and large samples can be prepared at low cost. Second, it is found that at 10 K plane-rolled $Tb_{0.60}Dy_{0.40}$ exhibits 1600 ppm magnetostriction at an applied field of 4.5 kOe with a minimal applied load of 0.28 MPa. The microstructural origin of this internal spring mechanism is under investigation, but it is likely related to elastic interactions between neighboring crystallites. Bulk thermal expansion measurements provide a rough measure of texture for comparison with the magnetostriction.

1. INTRODUCTION

In recent years there has been considerable interest in applying the large strains associated with magnetostrictive rare earths to low temperature actuator applications such as liquid helium valves, which operate at or below 4.2 K, and micropositioning devices for IR satellite optics, which operate at 50 K and below. Traditional actuator materials such as piezoelectrics perform poorly at and below liquid nitrogen temperatures. The advantages of having a cold prime mover are driving the push for low-temperature rare earth magnetostrictive actuators. The combination of magnetostrictive materials and high-T_c superconductors (HTSC) is a promising solution for low temperature actuation. TbDy alloys exhibit saturation magnetostrictions approaching 1.0% at low temperatures,[1] but the preparation of single crystals is difficult and costly. The Next Generation Space Telescope (NGST) may require 2000-3000 actuators in the next few years. Since it is not possible to produce single crystals in such numbers, textured polycrystals are being developed for use in actuator applications. Polycrystalline $Tb_{0.6}Dy_{0.4}$, cold rolled to induce crystallographic texture, has shown magnetostrictions at 10 K of 0.2%, and 0.3 % at 77 K. Even with this fraction of the single crystal performance, the polycrystalline samples have two major advantages. First, large samples can be prepared easily and at low cost. Second, polycrystalline TbDy alloys may not require an applied stress in order to return to an unstrained state. The use of the internal spring provided by the strain energy stored at the grain boundaries simplifies the engineering design of devices.

Materials Preparation and Costs

Since Tb has an easy <10-10> direction of magnetization while Dy has an easy <2-1-10>, an alloy ratio can be chosen to minimize the anisotropy in the basal plane for each temperature range of operation; for instance the estimated minima occur at $Tb_{0.76}Dy_{0.24}$ for 4 K, $Tb_{0.6}Dy_{0.4}$ for 77 K.[2] Preparation of hexagonal single crystals of TbDy is currently possible only by a strain anneal method, which is expensive and difficult to control. Because impurities inhibit grain growth, expensive high purity material is required for the single crystal growth process.[3] Commercial grade material has a total purity 99.7%, whereas the high purity material has a total purity of 99.94%.

For production of polycrystals, the TbDy alloy is arc melted. Since the as-cast ingot shows strong texture, the material is first deformed by 35% and heat treated for 1.5 hr at 950°C to induce recrystallization. This is thought to result in a somewhat more random initial orientation of spherical grains, although bulk thermal expansion measurements indicate that significant texture remains. The specimen was then form-rolled or plane-rolled by 55% and heated to 350°C in order to relieve strain. The texture of the material is critical due to the elastic interactions of misaligned grains and the large anisotropy of the material. At liquid helium temperatures a 10 Tesla field produces less than a 10% deflection of the magnetization from the basal plane.[4] Deformation encourages the c-axis of the crystallites to be parallel to the applied stress direction, but does not discourage the basal planes from being rotated with respect to each other. The cost of preparation of the polycrystalline materials may be reduced from several thousand for a single crystal to a few hundred dollars.

Experimental Methods

At 10 K the materials were characterized with a low temperature test facility,[5] which measures displacement with a Polytec laser vibrometer . A load is applied via a mechanical system and measured with a strain gauge load cell, and the field is applied with a low T_C superconducting coil. For measurements at 77 K, the linear displacement is measured by a Capacitec capacitence gauge and the superconducting coil has been replaced with an electromagnet configured to produce fields up to 4.5 kOe. Under current configurations the maximum attainable applied loads vary with the size of the test specimen. The single crystal was measured along the b-axis and the polycrystals were measured along the rolling direction. Thermal expansion measurements were performed on one of two dilatometers in single pushrod mode. All measurements were made from 30°C to at least 300°C under inert atmosphere to prevent oxidation.

Material Performance

At 10 K a b-axis single crystal $Tb_{0.6}Dy_{0.4}$ exhibits 8800 ppm magnetostriction at a field of 3 kOe with an applied stress of 27.5 MPa, as previously reported.[5] At 77 K magnetostrictions on the order of 6300 ppm are found.[3] The textured polycrystalline specimens require higher fields to saturate the material than can presently be produced in the test apparatus, although improvements are currently underway. As shown in Figure 1 at 3.8 kOe, and with an applied stress of 22.6 MPa the form-rolled specimen shows a magnetostriction of 1850 ppm. For the same applied field the plane-rolled specimen exhibits 2100 ppm with a load of 13 MPa. The magnetostrictions observed are dependent on the texture of the polycrystal, and plane-rolled specimens are expected to give higher magnetostrictions than the form-rolled specimen shown here for the same field and applied load.

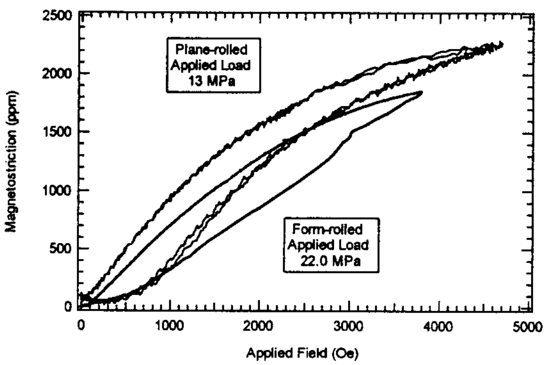

FIG. 1. Magnetostriction of $Tb_{0.6}Dy_{0.4}$ form-rolled and plane-rolled polycrystalline specimens.

As shown in Figure 2, with applied fields of 4.5 kOe, magnetostrictions of 2300 ppm are possible with an applied load of 13 MPa, as compared to 1600 ppm with a minimal applied load of 0.28 MPa at 10 K. Polycrystalline $Tb_{0.6}Dy_{0.4}$ does not require a large applied stress in order to return to an unstrained state, unlike single crystals. It is necessary to include preload stresses in the design of devices in order to make engineering use of the large magnetostrictions of the single crystals. The microstructural origin of this "internal spring" is likely related to elastic interactions between neighboring crystallites. It is possible that the need for a preload can be eliminated entirely by controlling the texture of the specimen.

Measurements were made at 77 K of both the form-rolled and plane-rolled magnetostrictions for fields of 4.5 kOe. For the form-rolled specimen, 1530 ppm was obtained at 2.8 MPa, which increased to 2450 ppm for a 27.6 MPa applied load. The plane-rolled specimen exhibited 1940 ppm at 2.1 MPa. At an applied load of 41 MPa the magnetostriction of the plane-rolled specimen was measured to be 3000 ppm or 48% of the single crystal value. The polycrystalline specimens

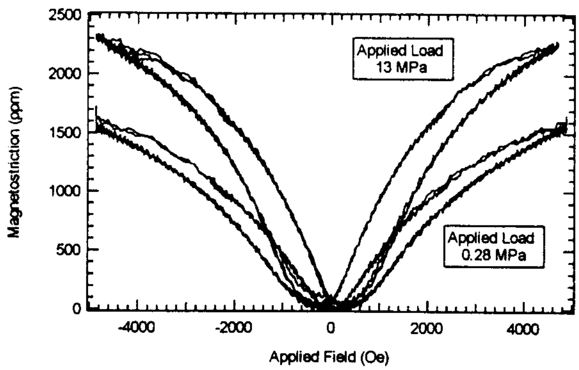

FIG. 2. Magnetostriction of a plane rolled polycrystalline specimen for applied load of 0.28 and 13.0 MPa at 10 K.

show larger magnetostrictions at 77 K than at 10 K even though the magnetostriction of the single crystals is monotonically increasing with decreasing temperature. This is likely related to both the internal stresses and the fact that as the temperature increased from 10 K to 77 K the $Tb_{0.6}Dy_{0.4}$ approaches its anisotropy minimum, and is currently under investigation.

Texture Determination by Thermal Expansion

As mentioned previously the texture is critical to the magnetostrictive performance of the material. It would be ideal to relate the bulk magnetostriction of the polycrystals directly to the crystallographic texture. This would involve X-ray determination of the full orientation distribution function (ODF). These materials do not lend themselves to this technique, however, due to the low X-ray penetration of the rare earths. The materials can still be characterized by X-ray methods if slices are taken through the specimen so that a full bulk texture determination can be approximated. This would be extremely time consuming and does not lend itself well to the correlation of magnetostriction and texture for a large number of specimens.

Above room temperature the thermal expansion of the rare earths is extremely anisotropic, with the expansion along the c-axis several times that along the a-axis. Previously reported values of the linear coefficient of thermal expansion for single crystal Tb (Dy), as determined by X-ray powder diffraction, are, for the c-axis direction, 17.9×10^{-6}/K (20.3×10^{-6}/K) and 9.1×10^{-6}/K (4.7×10^{-6}/K) for the a-axis at 673 K.[6] Elemental Tb and Dy single crystals were measured along the a- and c-axes. The linear coefficients of thermal expansion for Tb (Dy), are, for the c-axis direction, 14.5×10^{-6}/K (15.2×10^{-6}/K) and 3.8×10^{-6}/K (3.4×10^{-6}/K) for the a-axis single crystal.

The linear thermal expansion was measured for each of the $Tb_{0.6}Dy_{0.4}$ test specimens along the direction parallel to the magnetostriction measurement direction. The single crystal value was found to be 3.1×10^{-6}/K. The plane-rolled specimen showed 4.0×10^{-6}/K, while 4.5×10^{-6}/K was found for the form rolled specimen. Clearly the greater the deviation of the rod axis thermal expansion from the single crystal a-axis value the smaller the magnetostriction is.

Conclusion and Results

A textured polycrystalline material has been shown to exhibit magnetostriction 48% that of single crystals. It is expected that further tests will show that 48% of the single crystal value of $Tb_{0.76}Dy_{0.24}$, or 4200 ppm, is achievable at 10 K. Thermal expansion measurements are useful as an indicator of texture in these materials.

Acknowledgments

This research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Techonolgy, under contract with the National Aeronautics and Space Administration and at the California Institute of Technology. This work was supported under the Advanced Technology Development program with funds provided by the Microgravity Division. The single crystals were kindly furnished by Dr. Wun-Fogle of the Naval Surface Warfare Center in Silver Springs, MD. The authors are indebted to Dr. Clark for many helpful discussions. The single crystal and arc melted ingots were prepared by Dr. Lograsso at Ames Laboratory.

References

[1]M. L. Spano, A. E. Clark, J.P. Teter, J.R. Cullen, Jour. de Physique, **49**, 347, (1989).

[2]M. L. Spano, A. E. Clark, M. Wun-Fogle, IEEE Trans. Magn. **25**(5), 3794 (1989).

[3]A. E. Clark, M. Wun-Fogle, J. B. Restorff, J. F. Lindberg, IEEE Trans. Magn. **29**(6), 3511, (1993).

[4]J. J. Rhyne, A. E. Clark, J. Appl. Phys., **38**(3), 1379, (1967).

[5]J. A. Dooley, C. A. Lindensmith, R. G. Chave, B. Fultz, and J. Graetz, 6th International Conference on New Actuators Proceedings, 407, (1998).

[6]F. H. Spedding, J. J. Hanak, A. H. Daane, J. Less-Common Metals, **3**, 110, (1961).